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Hybrid Eulerian and Lagrangian Simulation of Steep and Breaking Waves and Surface Fluxes in High Winds

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LONG-TERM GOALS

This research aims at developing a hybrid numerical capability using a Lagrangian Smoothed Particle Hydrodynamics (SPH) method and an Eulerian Level-Set Method (LSM) for the simulation of steep and breaking waves in high winds. The ultimate goal is to establish an advanced computational framework for the investigation of wind-wave breaking in air-sea interaction processes, including the airflow separation over steep and breaking waves, the wind–wave momentum and energy transfer, the momentum and energy injection from breaking waves to the upper ocean, and the turbulence transport process.

OBJECTIVES

The scientific and technical objectives of this research are:

(1) develop a hybrid Eulerian and Lagrangian multi-fluids simulation capability, which combines the SPH and LSM with environmental input provided by coupled wind and wave simulations at far field;

(2) use the numerical method developed in (1) to simulate wind-wave-ocean interactions at small scales to elucidate flow structure;

(3) quantify and characterize wind–wave momentum and energy transfer and the injection to the upper ocean by breaking waves; and

(4) simulate and identify key process in turbulence transport near steep and breaking waves.

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APPROACH

This research builds on a hybrid simulation approach that couples several Eulerian and Lagrangian methods for free-surface turbulence and wave simulation. In the far field, coupled wind and wave simulations are used to obtain wind turbulence and wavefield, with the phases of nonlinear waves resolved, to provide realistic environmental input for the simulation of breaking waves. Specifically, LES of air turbulence is performed by using a hybrid pseudo-spectral and finite-difference method on a boundary fitted grid that follows the ocean wave surface; a high-order spectral (HOS) method is used to capture all of the dynamically important nonlinear wave interactions in the wavefield; and the wind and wave simulations are dynamically coupled through a fractional step method with two-way feedbacks.

As a wave becomes steep, LSM in a subdomain that contains the steep/breaking wave is performed to better resolve the flow field. LSM uses a signed distance function, namely the level-set function, to represent the interface implicitly. The location where the level-set function has zero value denotes the air–water interface. In the simulation, air and water together are treated as a fluid system with varying density and viscosity. In LSM, the level-set function is advected by the flow subject to a Lagrangian-invariant transport equation. To preserve the distance-function property for the level-set function, re-initialization is performed during the simulation using a sub-cell fix method. A Coupled Level-Set Volume-of-Fluid (CLSVOF) method is employed to conserve the mass precisely.

When the wave breaks, the flow at the free surface may become very violent, air and water may be highly mixed, and drops and bubbles may be formed. To better resolve the detailed structures and to robustly capture the violent flow, the SPH method is used, which is ideal for the wave breaking problem as the motion of nodal points (i.e., smoothed particles) is tracked in a Lagrangian manner.

All the codes are parallelized using message passing interface (MPI) based on domain decomposition. For SPH, graphics processing unit (GPU) computing, which is highly efficient for particle methods, is used to speed up the simulation.

WORK COMPLETED

In FY2011, substantial developments have been made for the codes with extensive tests. Encouraging results have been obtained in preliminary simulations of steep and breaking waves under wind forcing, which include:

- Simulation of wind turbulence over prescribed steep water waves, with quantification of wind pressure forcing on steep waves.
- Simulation of the evolution from steep waves to breaking waves in wind field, with quantification of wave surface characteristics.
- Simulation of wave breaking process under wind forcing, with comparison of breaking waves under different wind speeds and analysis of the enhancement of near-surface turbulence by the splash up of breaking waves.
- Simulation of airflow separation associated with wave breaking, with illustration of air motion in separation bubble.

- LSM and SPH coupling in wave simulations, with comparison of the wave surface and velocity field between SPH and LSM.

RESULTS

During this reporting period, further developments have been made in the LSM and SPH simulations of wind and waves. Encouraging results have been obtained. First, wind turbulence above prescribed steep water waves at laboratory scales is simulated. Figure 1 shows the dynamic pressure in the air above the waves under different wind speeds. As expected, in all of the four cases shown, the pressure maximum is located on the windward surface of the wave and the minimum is on the leeward. The normalized pressure magnitude increases with the wind speed. As the wind speed increases, the pressure maximum moves toward the wave trough, the minimum moves toward the crest, and the low pressure bubble becomes flatter.

For waves that have large amplitude initially and evolve dynamically under the wind forcing in our simulation, Figure 2 shows the instantaneous water surface and the streamwise velocity field on two vertical planes. Four cases with different wind speeds are considered. It can be seen that wind strongly affects the breaking of surface waves. As the wind speed increases, the breaking happens earlier and appears more violent as expected. The breaking also affects the turbulence in the wind. In Figure 2(d), the enhancement of turbulent mixing in the airflow due to the splash up near the breaking crest is observed.

Airflow separation, which usually occurs with steep and breaking waves, has been considered as a key process in the momentum exchange between wind and waves. In figure 3, the flow field at the onset of wave breaking is plotted. At this moment, the wave crest just starts to overturn, the velocity at the crest front exceeds the wave phase speed, and airflow separation happens. In figure 3(b), the velocity vectors around the breaking crest are plotted, which show a highly turbulent flow region above the wave trough. In figure 3(c), contours of streamwise velocity are plotted, and a large region of reversal flow can be seen. In figure 3(d), streamlines are plotted, which show the separation bubble after the breaking crest.

We have also simulated the complete process of wave growing and breaking under wind forcing, starting from a wave with mild slope. In figure 4, the wave surface at four different instances in the wave evolution process is plotted. At the early stage of $t \approx 0.6T$, the wind turbulence disturbs the water surface and generates small scale surface structures riding on the dominant wave. As the wind continues blowing, the amplitude of the dominant wave increases, the nonlinear wave effect becomes significant, and the wave crest becomes sharper at $t \approx 1.2T$. At $t \approx 1.8T$, the crest of the dominant wave splits into two and the one behind becomes very steep. At $t \approx 2.4T$, the dominant wave crest overturns and the wave breaks.

The coupling of LSM and SPH is under development. Figure 5 shows the result of a coupled simulation, in which LSM simulation provides boundary condition to the SPH simulation in a sub-domain. For the test with surface wave propagation, the free surface and the velocity field match well between the LSM and SPH simulations. We are currently performing validation with wave breaking.

IMPACT/APPLICATION

This project aims at developing an advanced simulation tool for multi-fluids free-surface flows that can be used to study the fundamental physics of wave breaking. The research will improve the understanding of air-sea interaction dynamics. The numerical developments in this project are expected to substantially improve the accuracy and efficiency of breaking wave simulation, which will lead to a powerful computational capability for direct comparison of measurement and modeling.

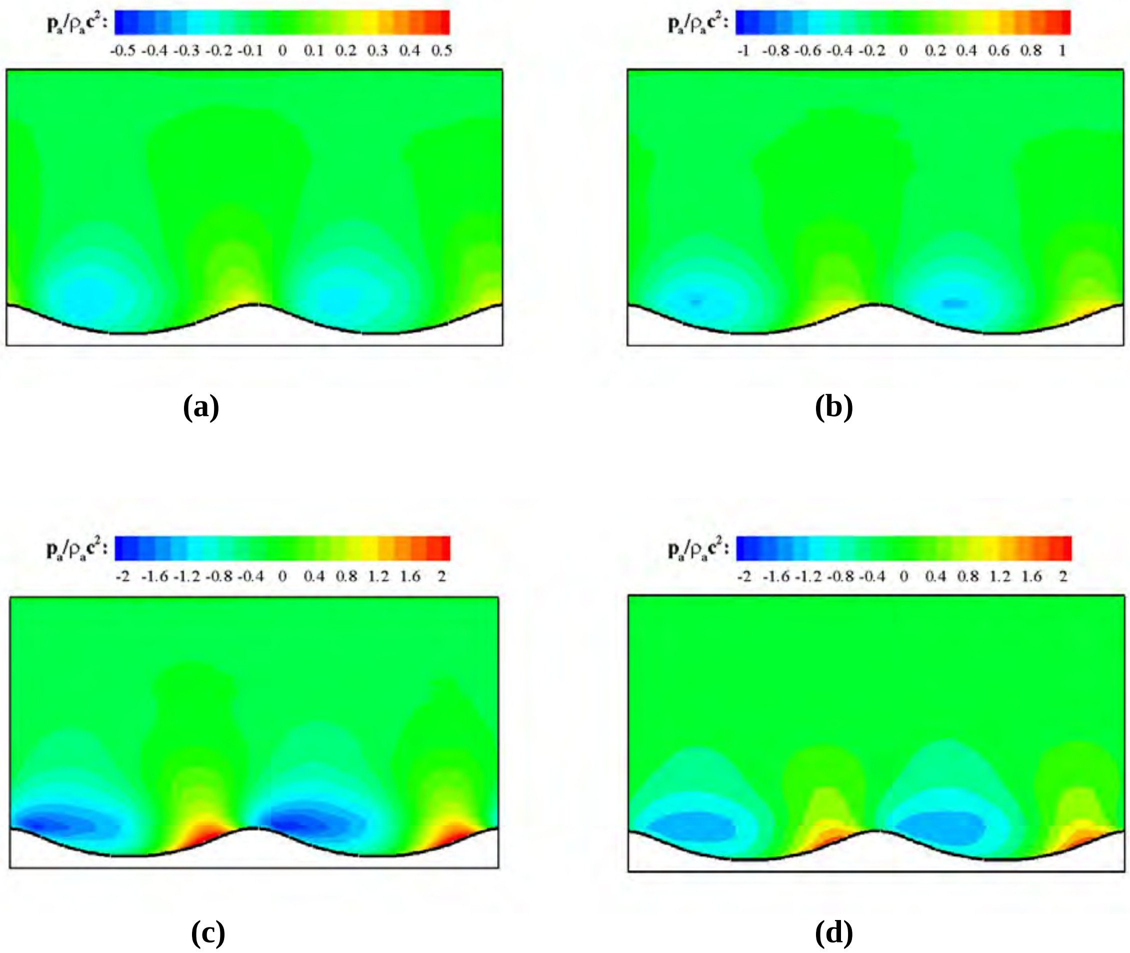


Figure 1. Phase- and spanwise-averaged dynamic pressure field of turbulent wind over a prescribed 3rd-order Stokes wave (with wavelength 0.262m and wave slope 0.35***): (a)*** $U_{10} = 3.5\ m/s$ ***; (b)*** $U_{10} = 6.0\ m/s$ ***; (c)*** $U_{10} = 7.9\ m/s$ ***; (d)*** $U_{10} = 10.0\ m/s$ ***. Here,*** U_{10} ***is the mean wind speed at 10 meter height above the mean water level. The pressure is normalized by*** $\rho_a c^2$***, with*** ρ_a ***and*** c ***being the air density and wave celerity, respectively.***

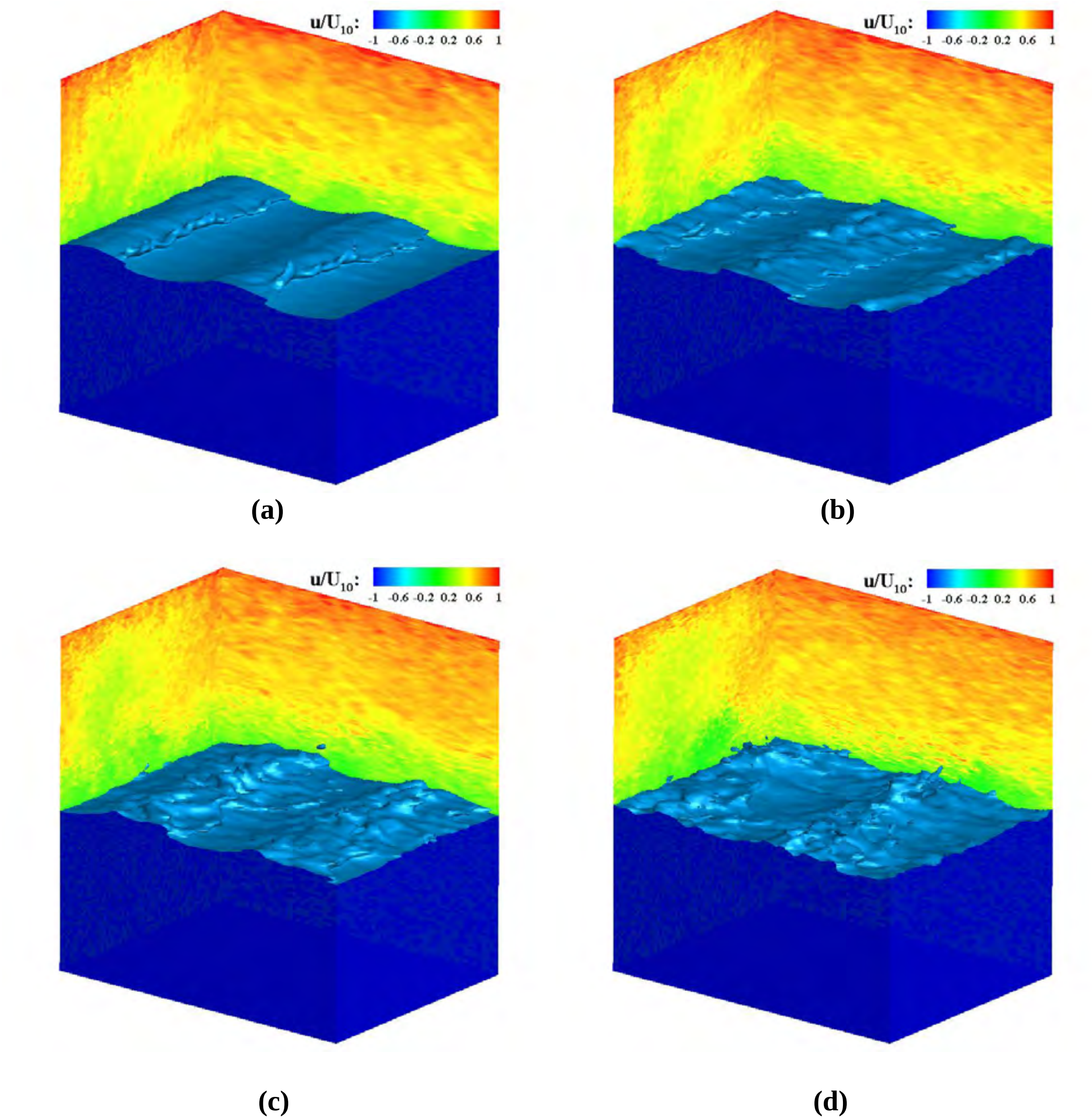
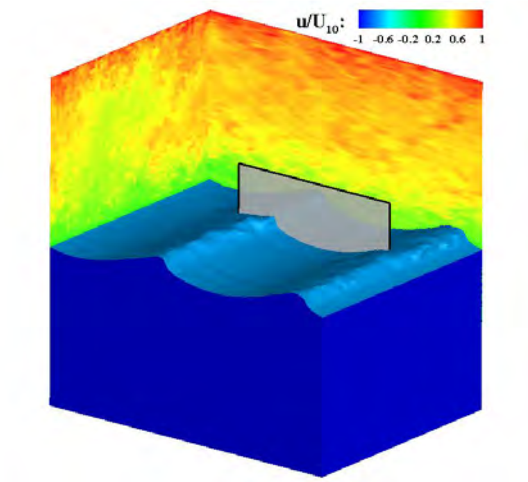
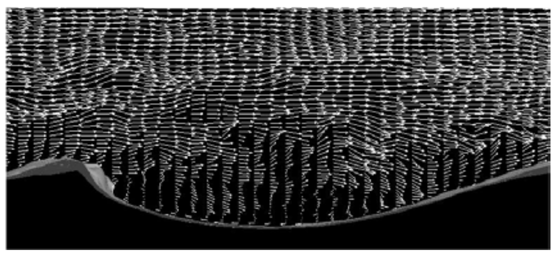


Figure 2. Instantaneous streamwise velocity of turbulent wind and water surface of a wave that has wavelength 0.262m and wave slope 0.35 ***initially and then evolves dynamically under the forcing of wind of: (a)*** $U_{10} = 3.5\ m/s$***; (b)*** $U_{10} = 6.0\ m/s$***; (c)*** $U_{10} = 7.9\ m/s$***; (d)*** $U_{10} = 10.0\ m/s$ ***. Here,*** U_{10} ***is the mean wind speed at 10 meter height above the mean water level.***
The result at $t = 0.417s \approx 1T$ ***is plotted.***



(a)



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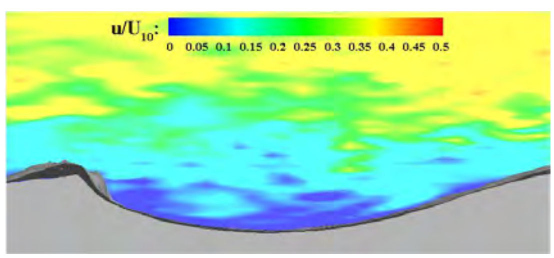
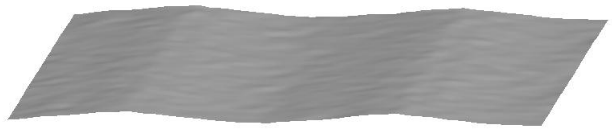


(c)

(d)

Figure 3. Instantaneous airflow field at the onset of wave breaking: (a) the contours of streamwise velocity on two vertical planes and the water surface; and (b) the velocity vectors, (c) the streamwise velocity contours, and (d) the streamlines on the small cut shown in (a). The wave has wavelength 0.262m and wave slope 0.35 initially and then evolves dynamically under the forcing of a wind of $U_{10} = 3.5\ m/s$. Here, U_{10} is the mean wind speed at 10 meter height above the mean water level. The result at $t = 0.24s \approx 0.58T$ after the wave release is plotted. T is the wave period.



(a)

(b)

(c)

(d)

Figure 4. Instantaneous water surface of an initially mild wave driven by turbulent wind at: (a) $t = 0.24s \approx 0.6T$ ***; (b)*** $t = 0.48s \approx 1.2T$ ***; (c)*** $t = 0.72s = 1.8T$ ***; (d)*** $t = 0.96s = 2.4T$ ***. The wave has wavelength 0.262m and wave slope*** 0.1 ***initially and then evolves dynamically under the forcing of a wind of*** $U_{10} = 3.5\ m/s$ ***. Here,*** T ***is the period of the dominant wave;*** U_{10} ***is the mean wind speed at 10 meter height above the mean water level.***

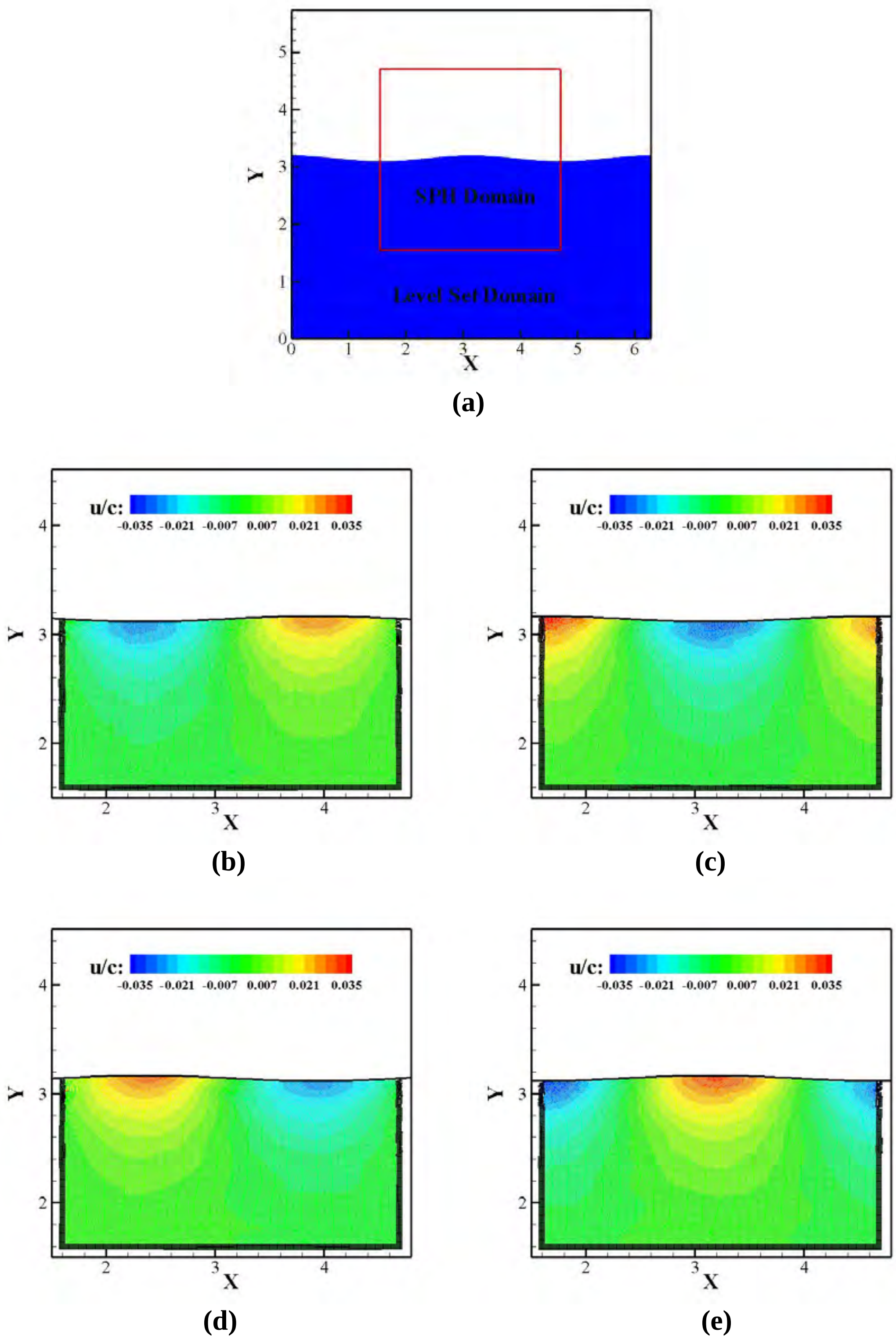


Figure 5. Coupled LSM/SPH simulation of a water wave with slope 0.05: (a) sketch of the setup for the coupled simulation; and contours of horizontal velocity(normalized by wave phase speed c) obtained from SPH simulation and the corresponding free surface obtained from LSM simulation at (b) $t = 4.25T$ ***; (c)*** $t = 4.5T$ ***; (d)*** $t = 4.75T$ ***; (e)*** $t = 5.0T$ ***. Here,*** T ***is the wave period.***